

MiniBooNE Cross Section Results

W. C. Louis

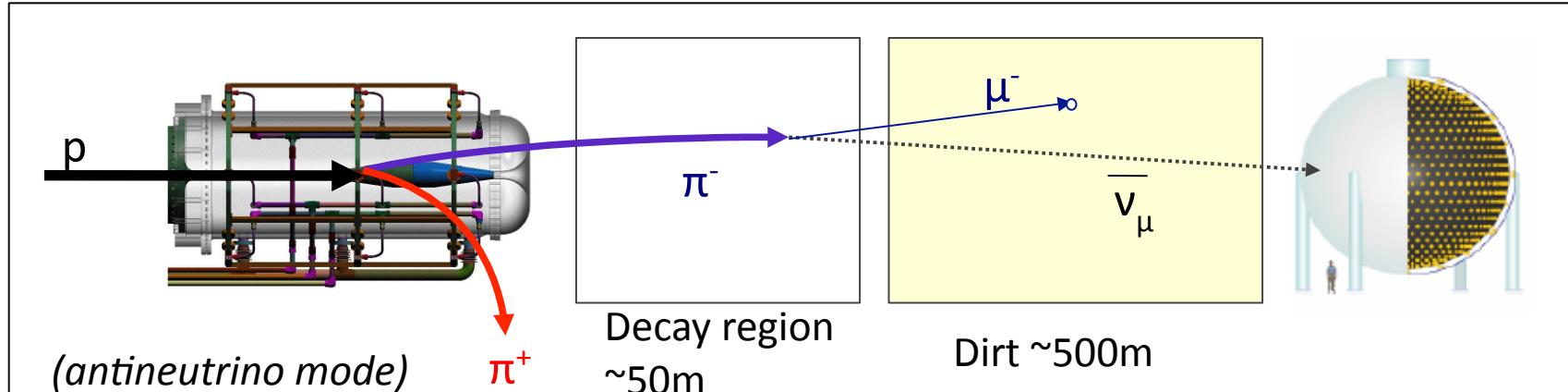
Los Alamos National Laboratory

NuFACT11, August 1, 2011

Outline

- MiniBooNE Description
- CC QE
- NC Elastic
- NC & CC π^0
- CC π^+
- Conclusions

MiniBooNE Experiment



- Similar L/E as LSND
 - MiniBooNE ~500m/~500MeV
 - LSND ~30m/~30MeV
- Horn focused neutrino beam ($p+Be$)
 - Horn polarity \rightarrow neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

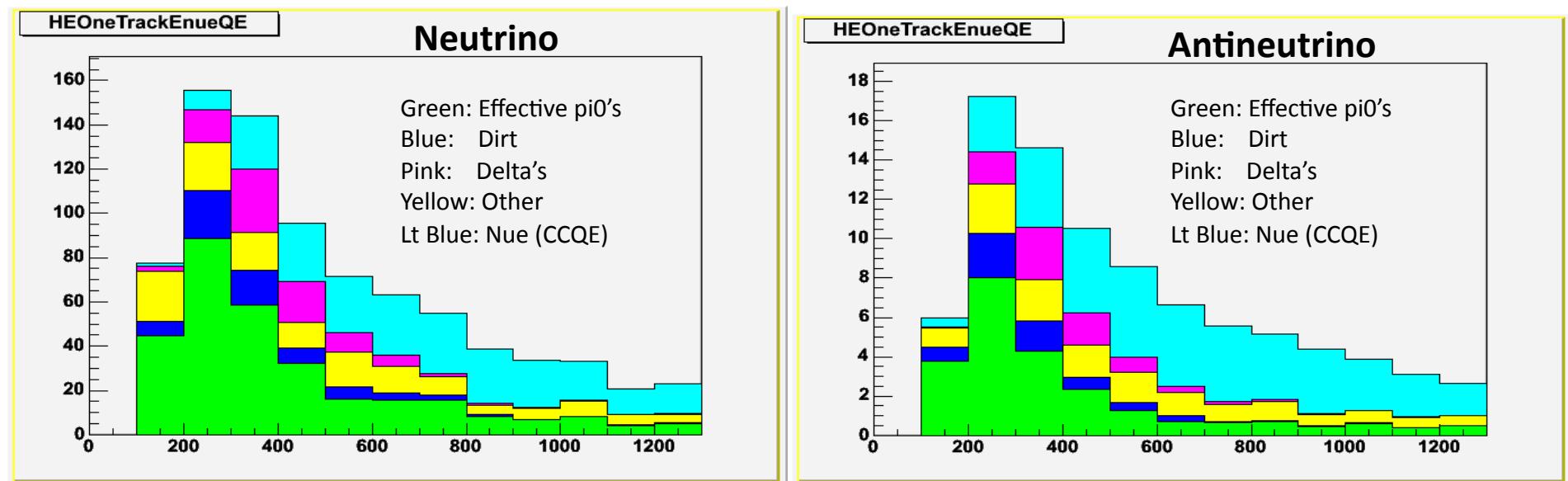
ν Event Rate Predictions

$$\# \text{Events} = \text{Flux} \times \text{Cross-sections} \times \text{Detector response}$$

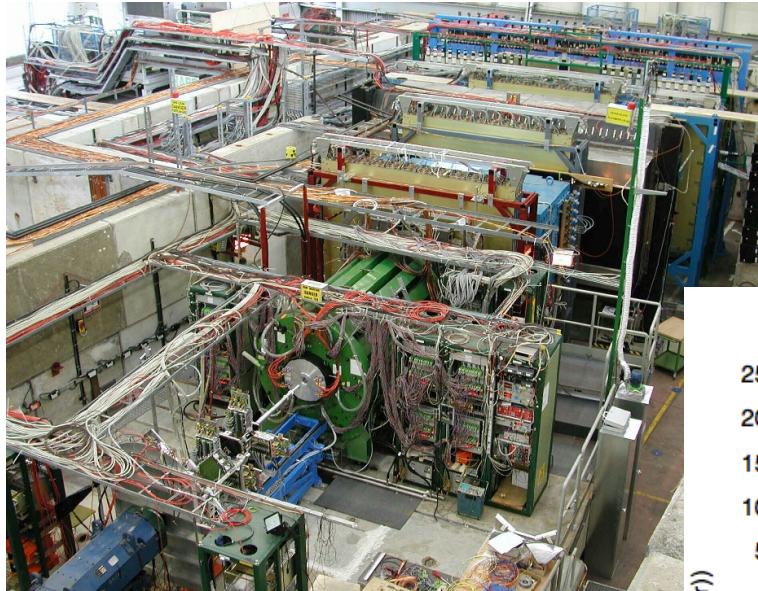
**External measurements
(HARP, etc)**
 ν_μ rate constrained by neutrino data

External and MiniBooNE measurements
- π^0 , delta and dirt backgrounds constrained from data.

Detailed detector simulations checked with neutrino data and calibration sources.



Modeling Production of Secondary Pions

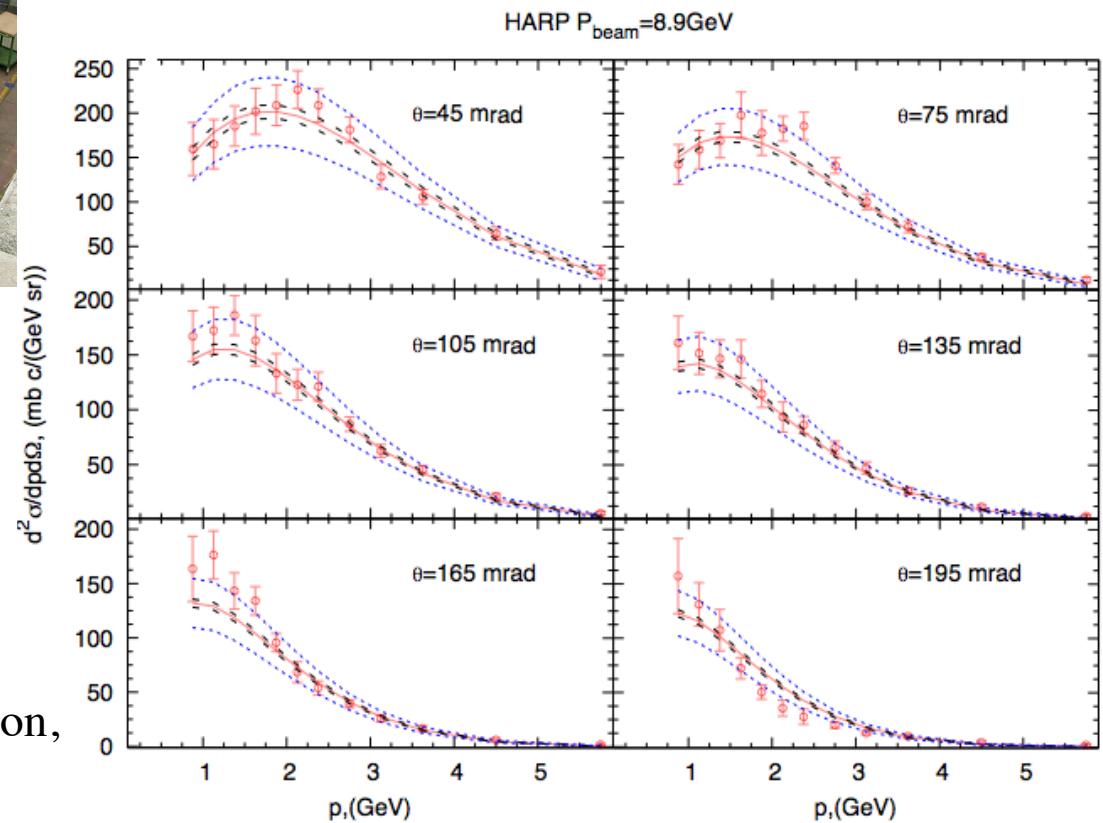


Data are fit to
a Sanford-Wang
parameterization.

HARP collaboration,
hep-ex/0702024

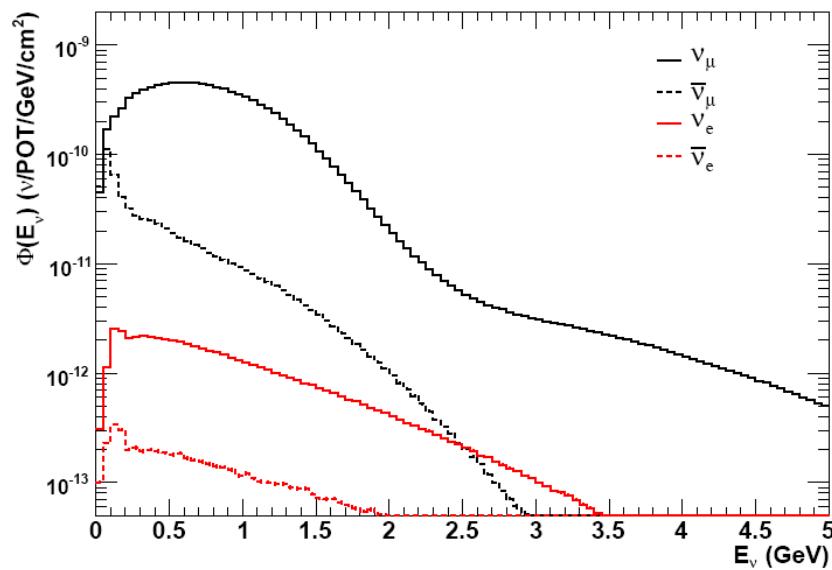
- HARP (CERN)

- 5% λ Beryllium target (good approximation)
- 8.9 GeV proton beam momentum
- π^+ & π^-

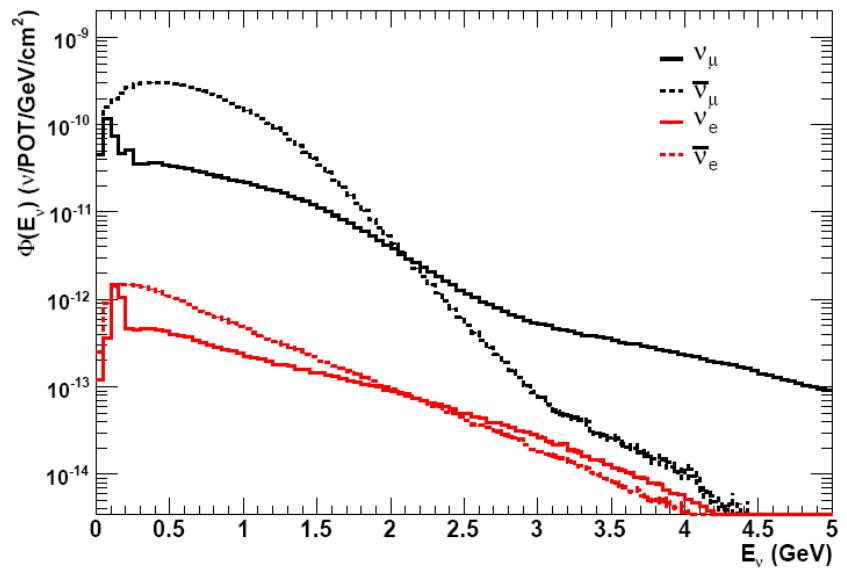


Neutrino Flux from GEANT4 Simulation

Neutrino-Mode Flux



Antineutrino-Mode Flux

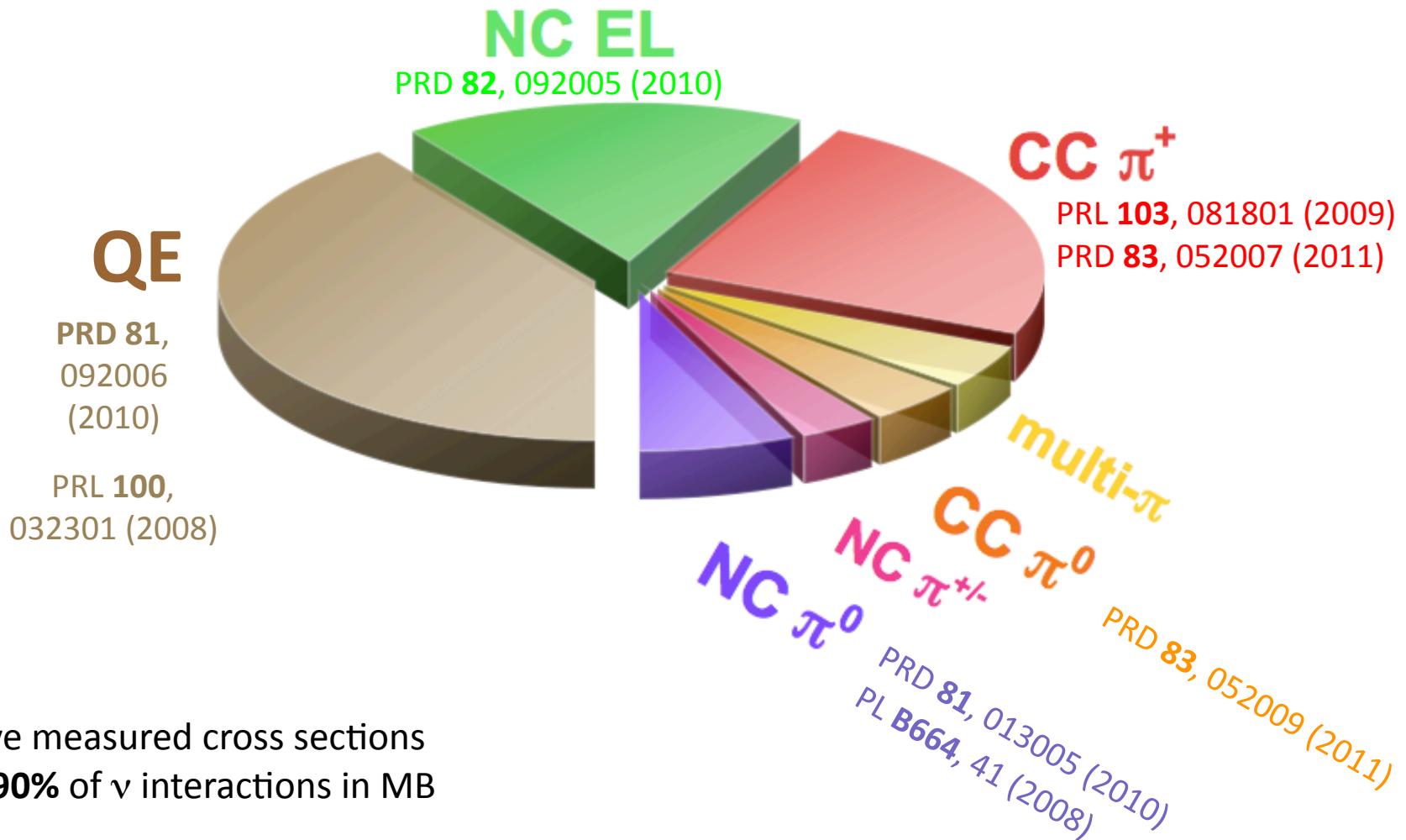


Wrong-sign background is ~6% for Nu-Mode & ~18% for Antinu-Mode
Intrinsic ν_e background is ~0.5% for both Nu-Mode & Antinu-Mode

Neutrino Cross Sections

- 8 neutrino cross section publications

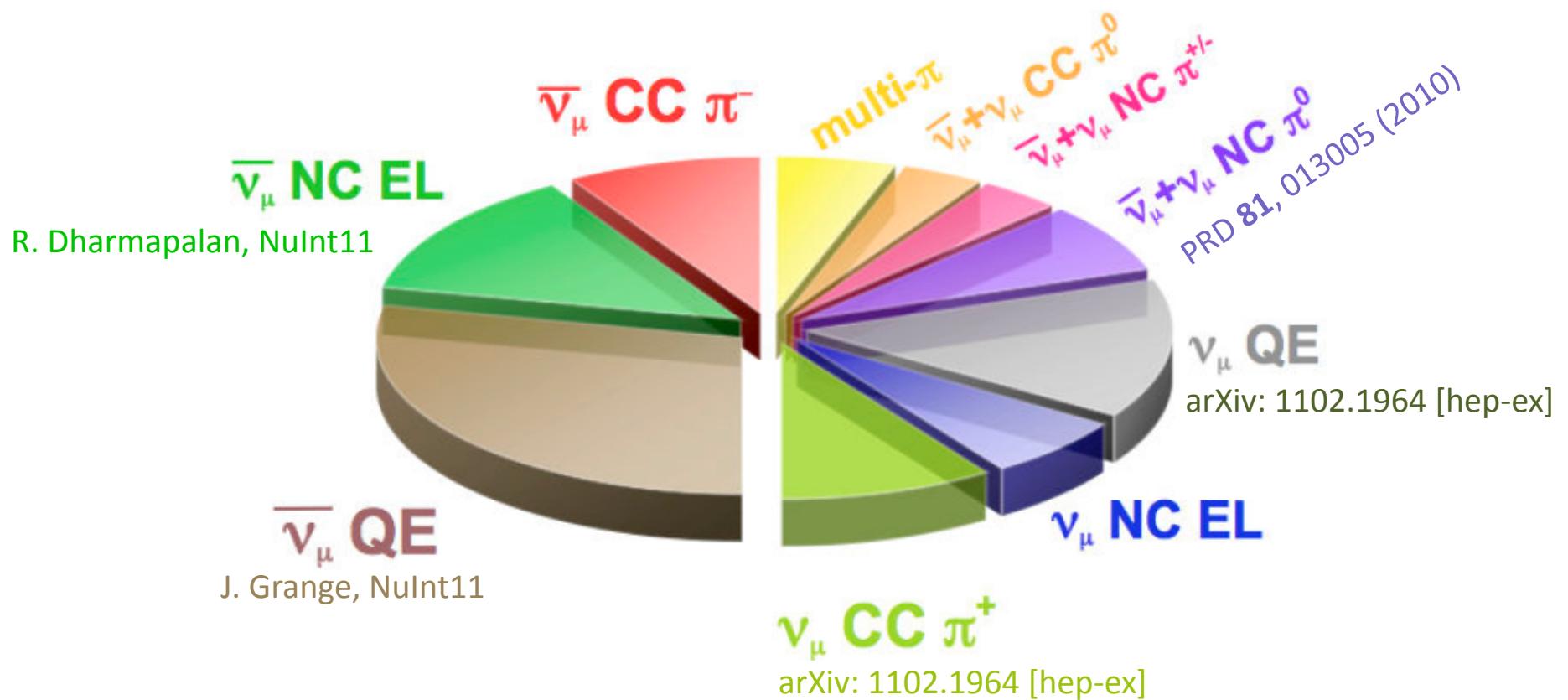
(NUANCE)



- have measured cross sections for **90%** of ν interactions in MB

Antineutrino Cross Sections

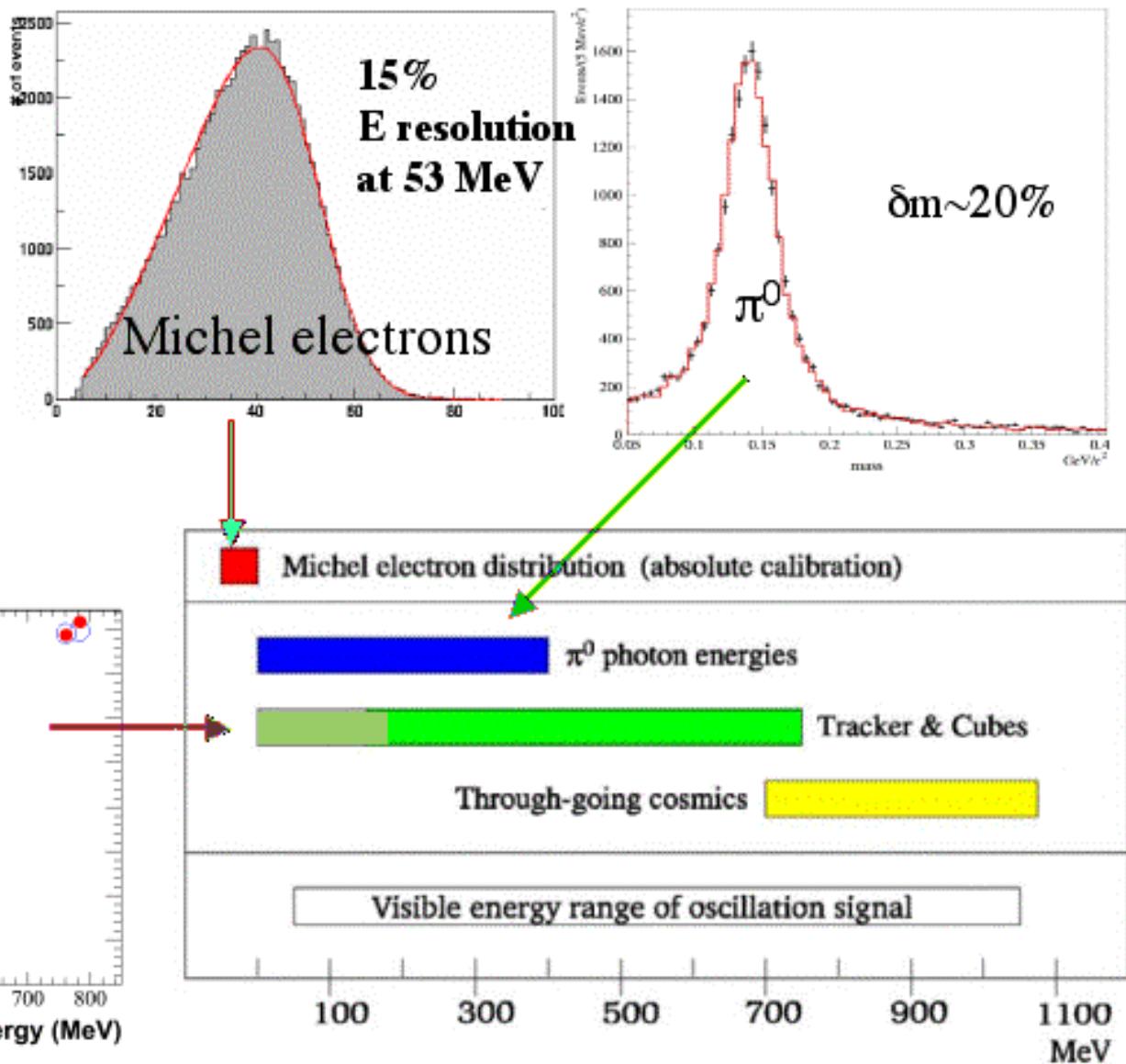
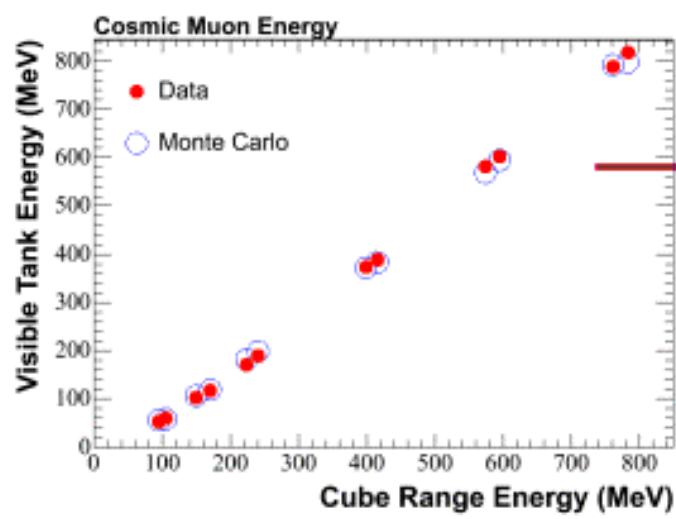
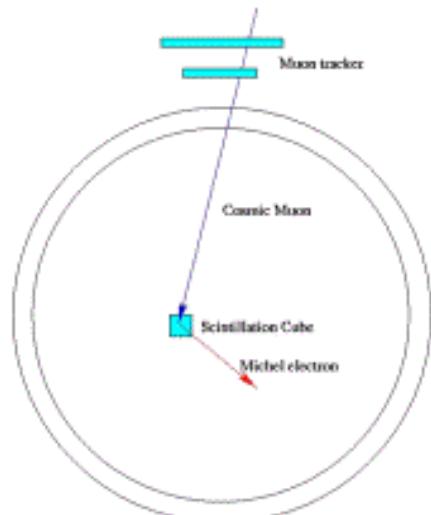
- 2 antineutrino cross section papers



- additional antineutrino analyses currently underway

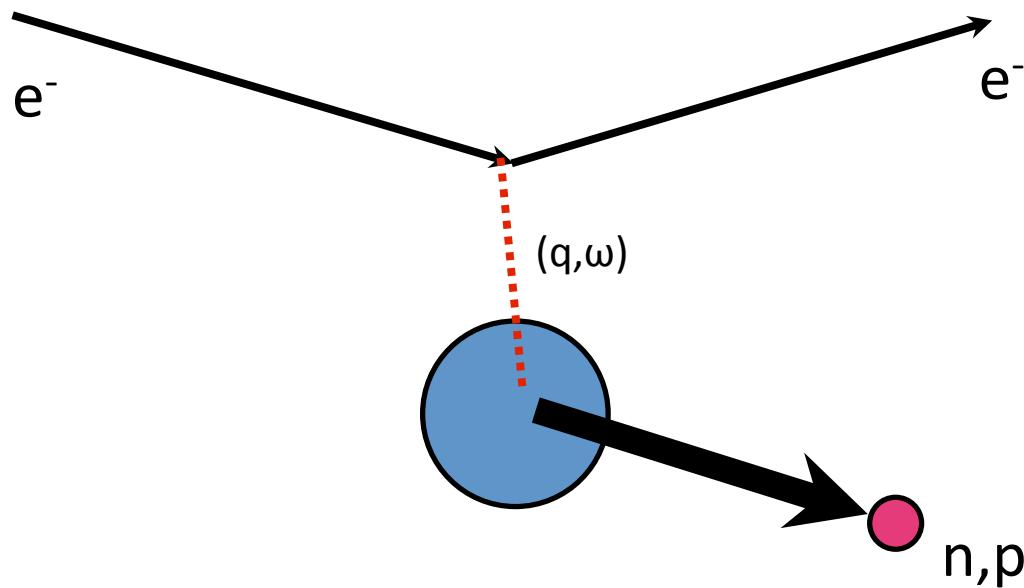
Calibration Sources

Tracker system



Quasi-Elastic Scattering

Originated in electron-nucleus scattering, where inclusive electron scattering is expected to be dominated by knocking a single (**unmeasured**) nucleon out of the nucleus

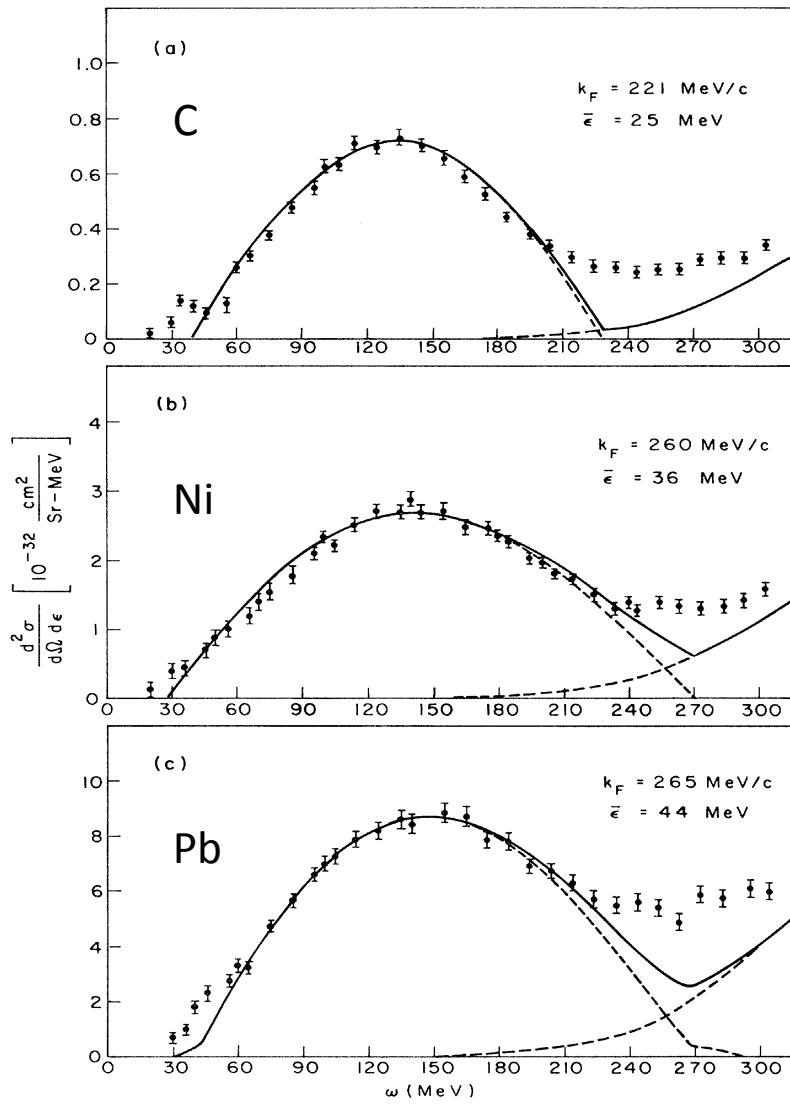


Expect similar response from almost all nuclei,
characterized by initial momentum distribution

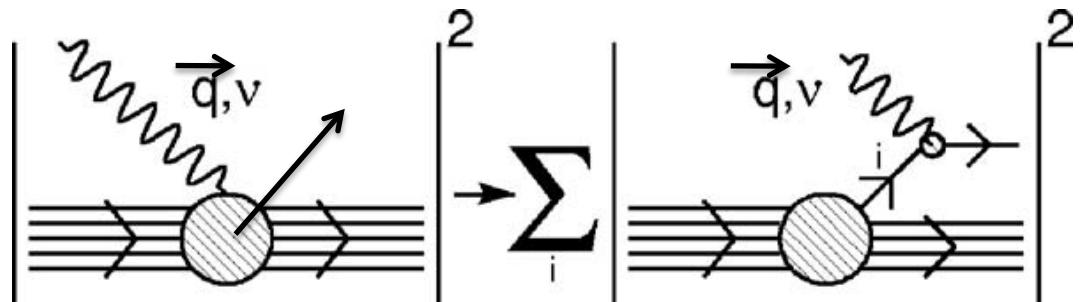
From Joe Carlson

Simple Fermi-Gas Model Appeared to Explain the Data Well

Moniz et al PRL 1971



Impulse Approximation



Quasi-Elastic Kinematics

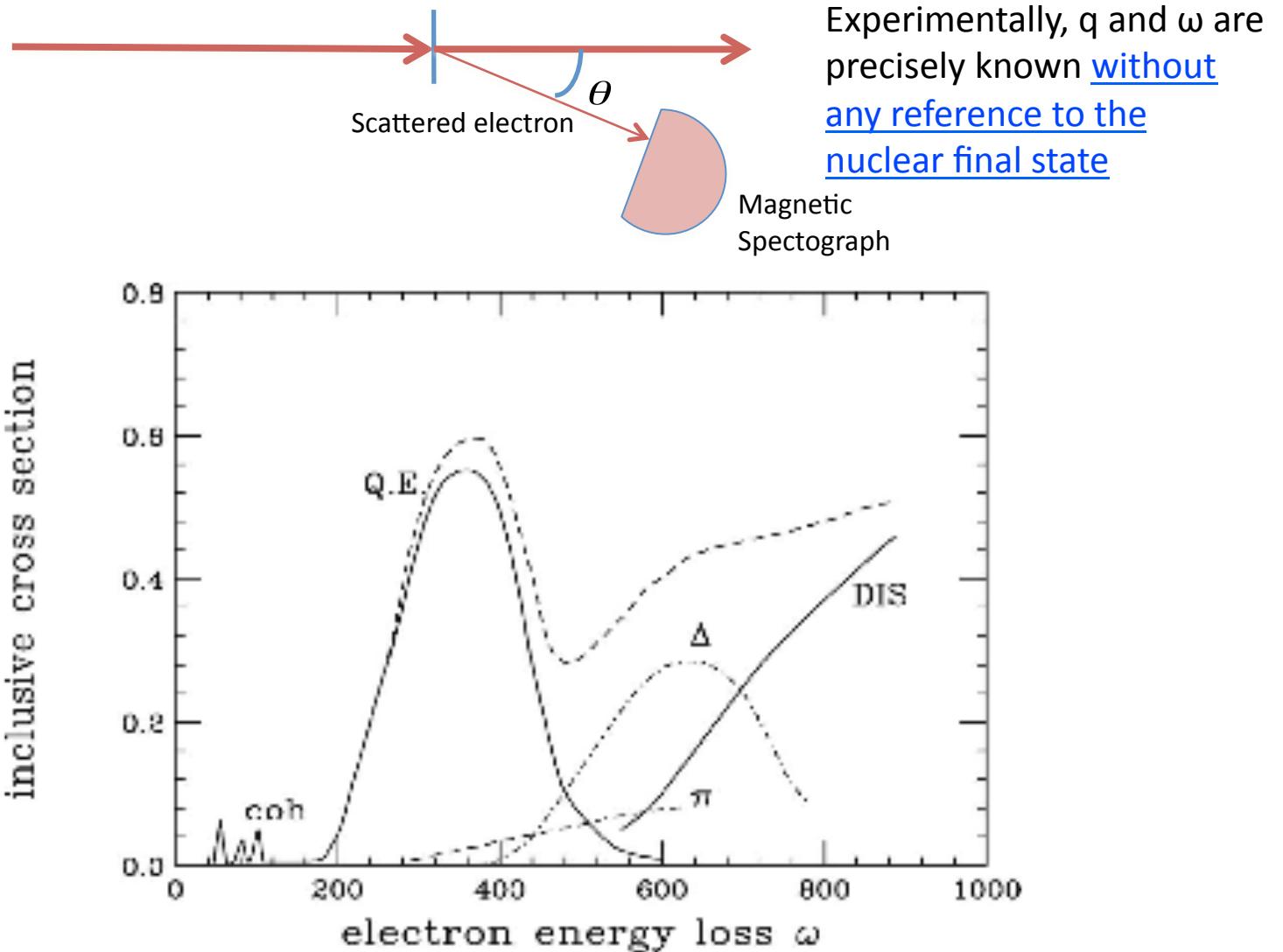
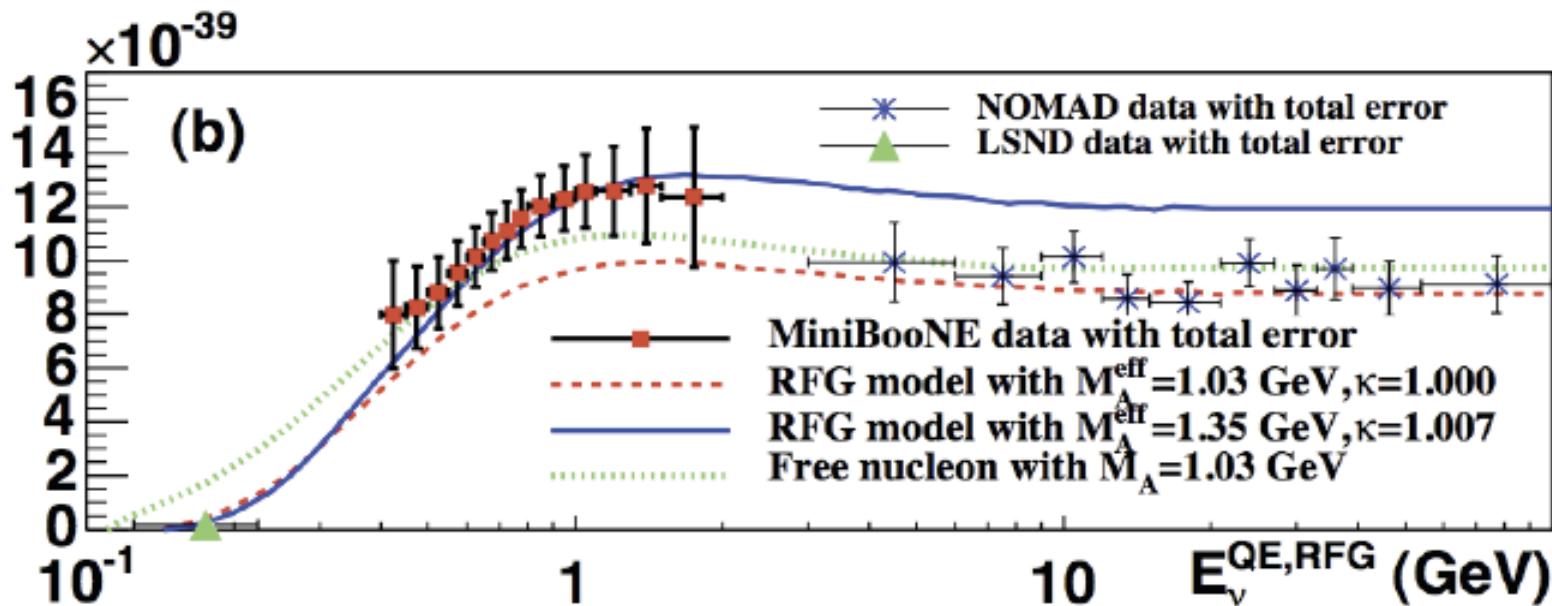


FIG. 1. Schematic representation of inclusive cross section as a function of energy loss.

From Joe Carlson

ν_μ CCQE Scattering

A.A. Aguilar-Arevalo, Phys. Rev. D81, 092005 (2010).

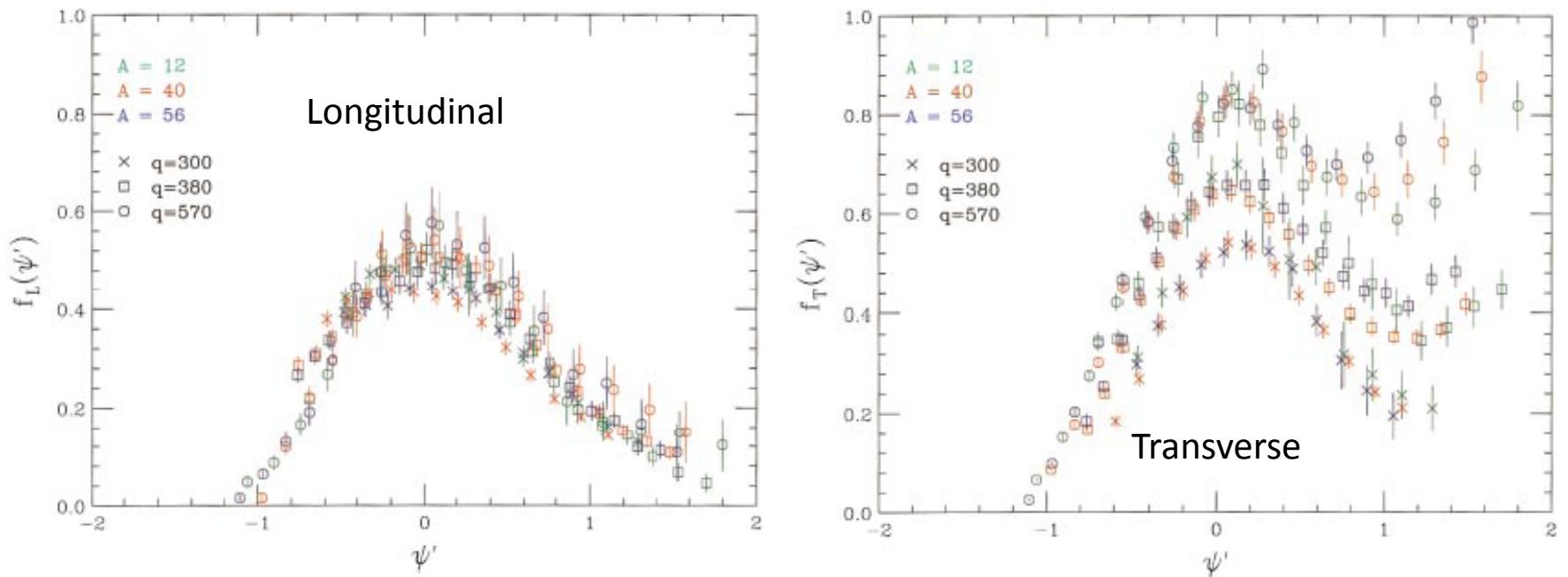


Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}\text{C}) > 6 \sigma_{\nu\mu}(\text{n})$

How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys. Rev. C65, 024002 (2002); Martini et al., PRC80, 065001 (2009).

Look more carefully at electron scattering: Enhancement of Transverse Responses Phys. Rev. C60, 065502 (1999)



Longitudinal scattering weakly dependent upon nucleus and momentum transfer

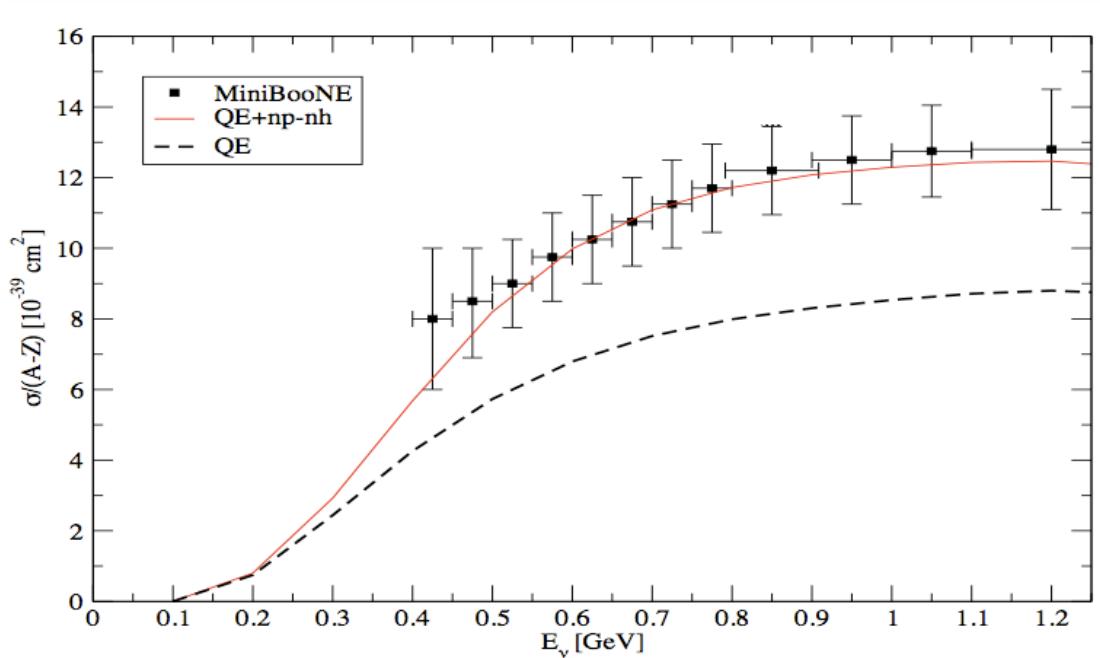
Transverse response depends dramatically upon q^2 (up to $\sim 50\%$): not reproduced in FG model!

Transverse also nearly independent of nucleus.

From Joe Carlson

Nuclear Effects to the Rescue?

- possible explanation: extra contributions from two-nucleon correlations in the nucleus (all prior calculations assume independent particles)

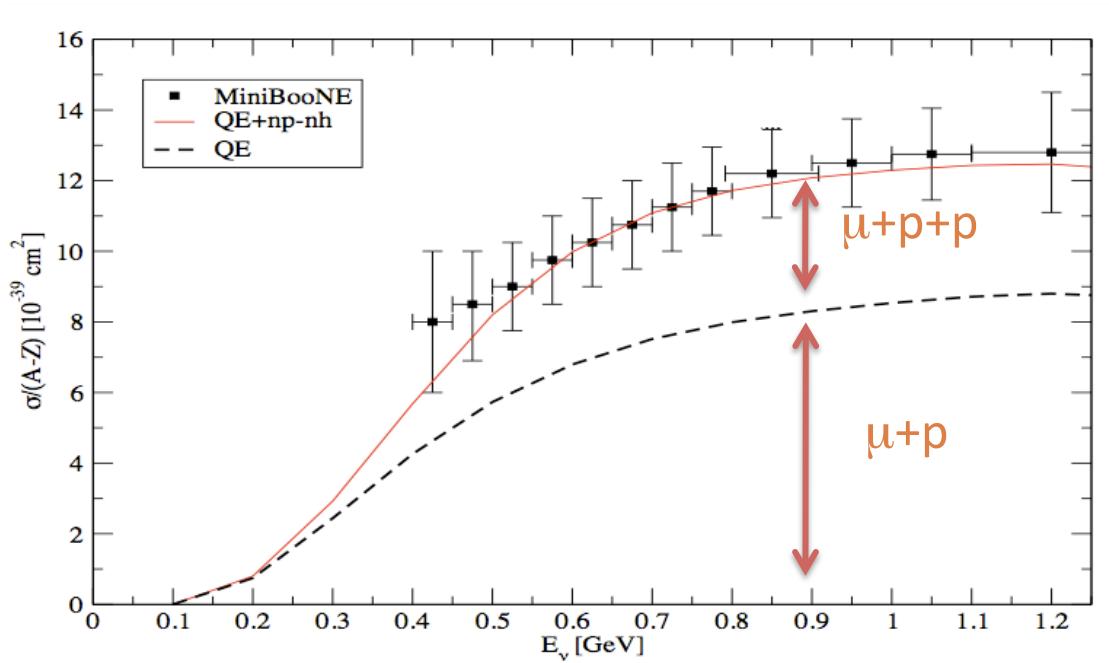


Martini *et al.*, PRC 80, 065001 (2009)

- large enhancement from short range correlations (SRC)
- can predict MiniBooNE data without having to increase M_A (here, $M_A=1.0$ GeV)

Nuclear Effects to the Rescue?

- possible explanation: extra contributions from two-nucleon correlations in the nucleus (all prior calcs assume indep particles)



Martini *et al.*, PRC 80, 065001 (2009)

- could this explain the difference between MiniBooNE & NOMAD?

NOMAD: μ & $\mu + p$

MiniBooNE: μ + no π 's
+ any # p's

jury is still out on this

need to be clear
what we mean by “QE”

Comparisons to MB Double Diff'l σ

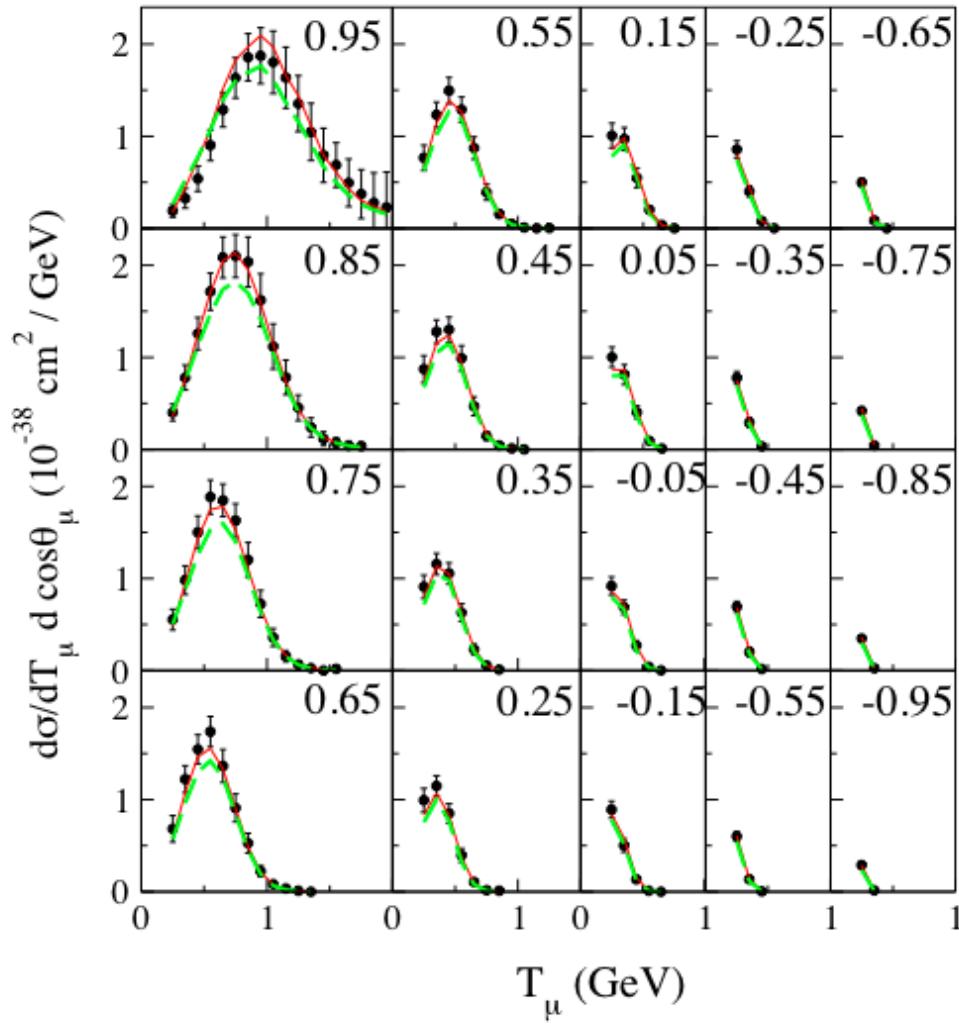


FIG. 1. Muon angle and energy distribution $d\sigma/d\cos\theta_\mu dT_\mu$. Different panels correspond to the various angular bins labeled by their cosinus central value. Experimental points from Ref. [8]. Green-dashed line (no fit) is the full model (including multinucleon mechanisms and RPA) and calculated with $M_A = 1.049$ GeV. Red-solid line is best fit ($M_A = 1.32$ GeV) for the model without RPA and without multinucleon mechanisms.

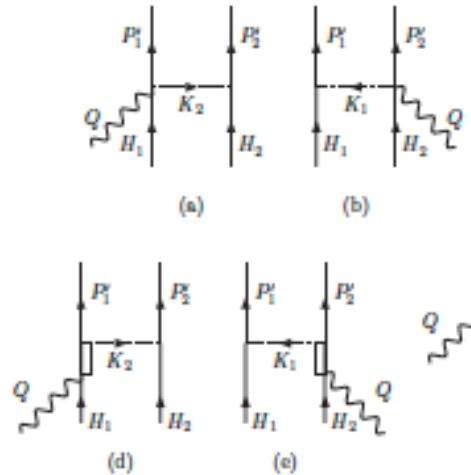
Nieves, Simo, & Vacas,
arXiv:1106.5374

Accounts for long range
nuclear correlations &
multinucleon scattering
with $M_A = 1.049$ GeV

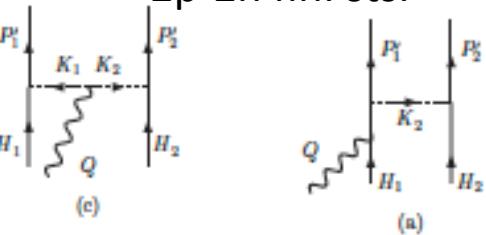
Is the Neutrino Energy Estimated Correctly in CCQE?

Amaro, et al, PHYSICAL REVIEW C 82, 044601 (2010)

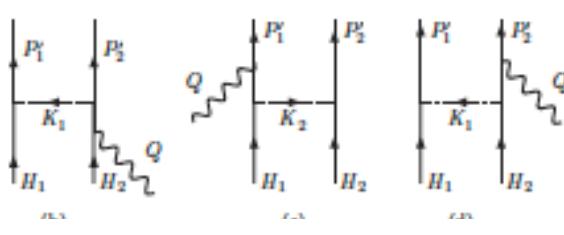
Meson Exchange Diags.



2p-2h fin. sts.

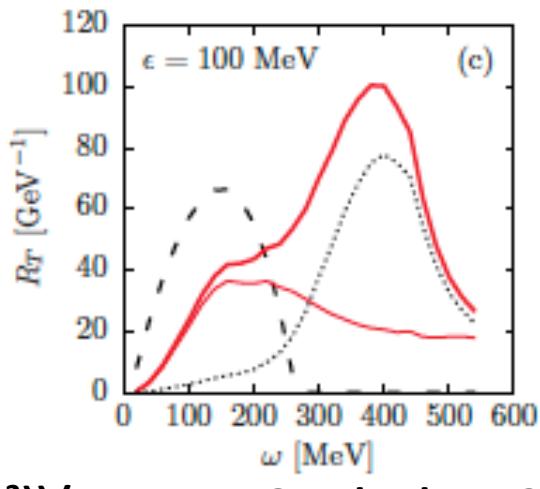


Correlation Diags.



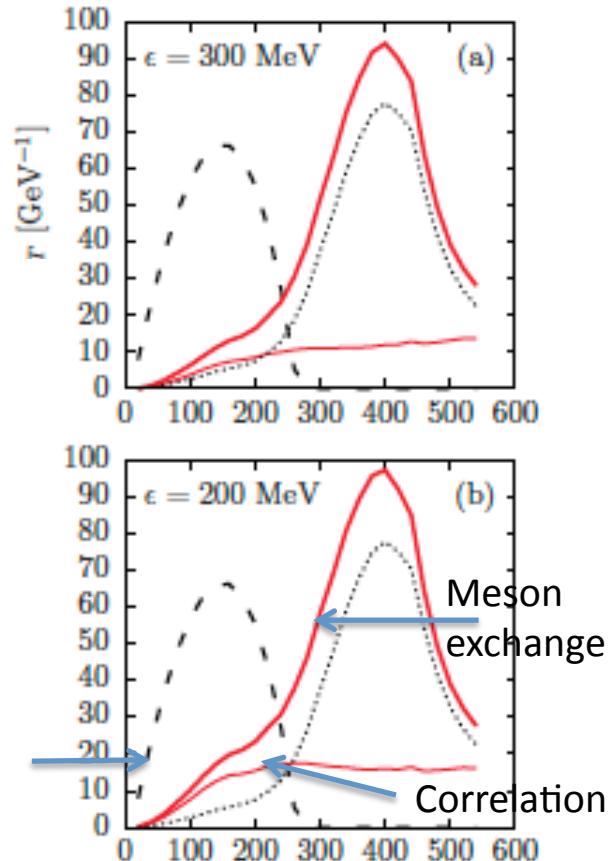
Electron Scattering

^{56}Fe , $q=0.55\text{GeV}/c$

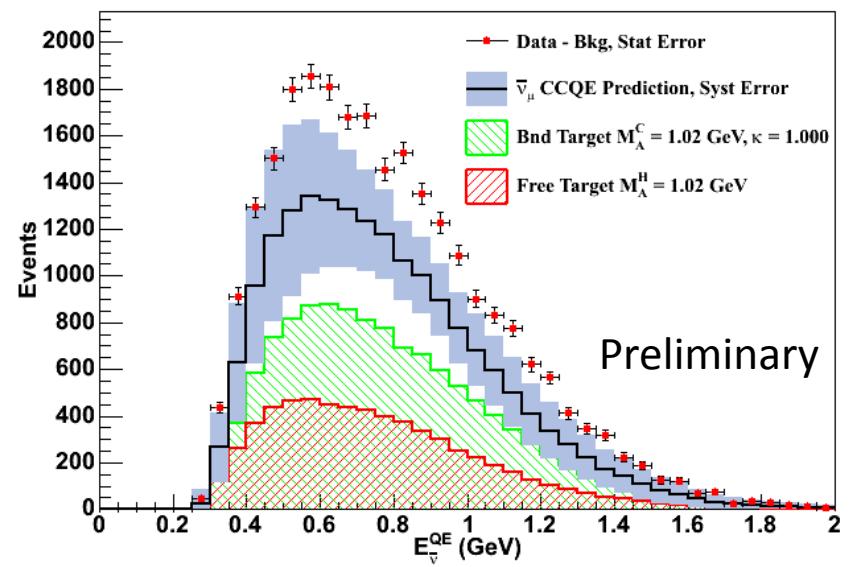
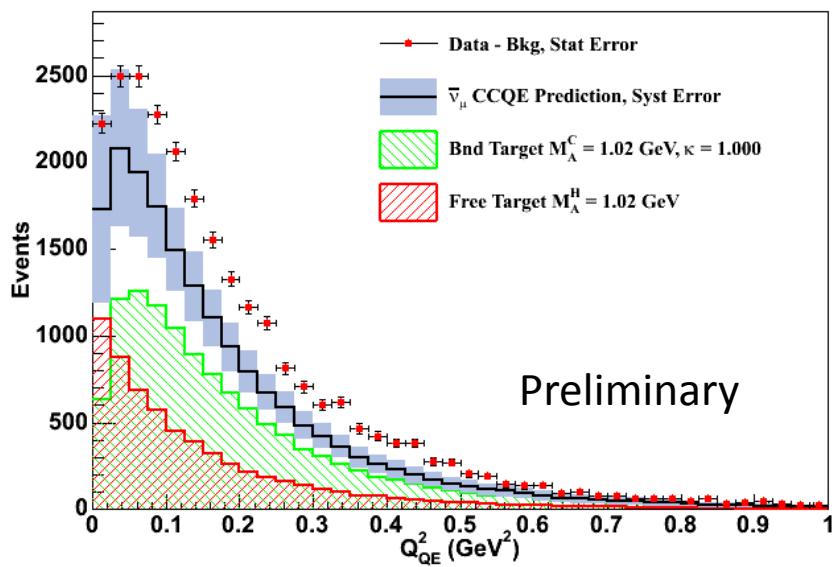


One body RFG

$$E_{\nu}^{\text{QE}} = \frac{(2m'_n E_{\mu} - (m'_n{}^2 + m_{\mu}{}^2 - m_p{}^2))}{2. / (m'_n - E_{\mu} + \sqrt{E_{\mu}{}^2 - m_{\mu}{}^2} \cos(\theta))}$$



$\bar{\nu}_\mu$ CCQE Scattering



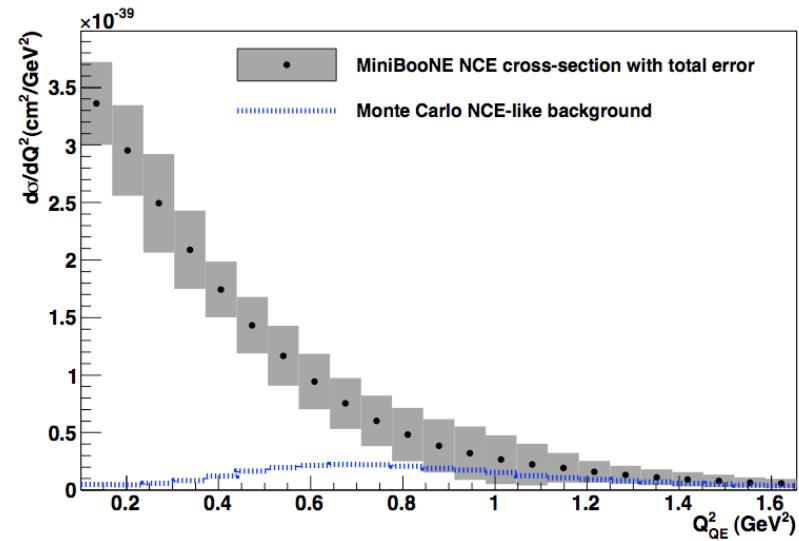
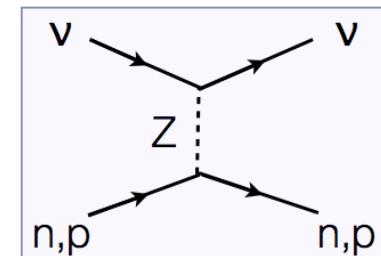
Enhancement also observed in antineutrino scattering
 Data/MC integrated ratio: 1.39 ± 0.14

J. Grange, NuINT11

Neutrino Neutral Current Elastic

Phys.Rev.D82:092005,2010

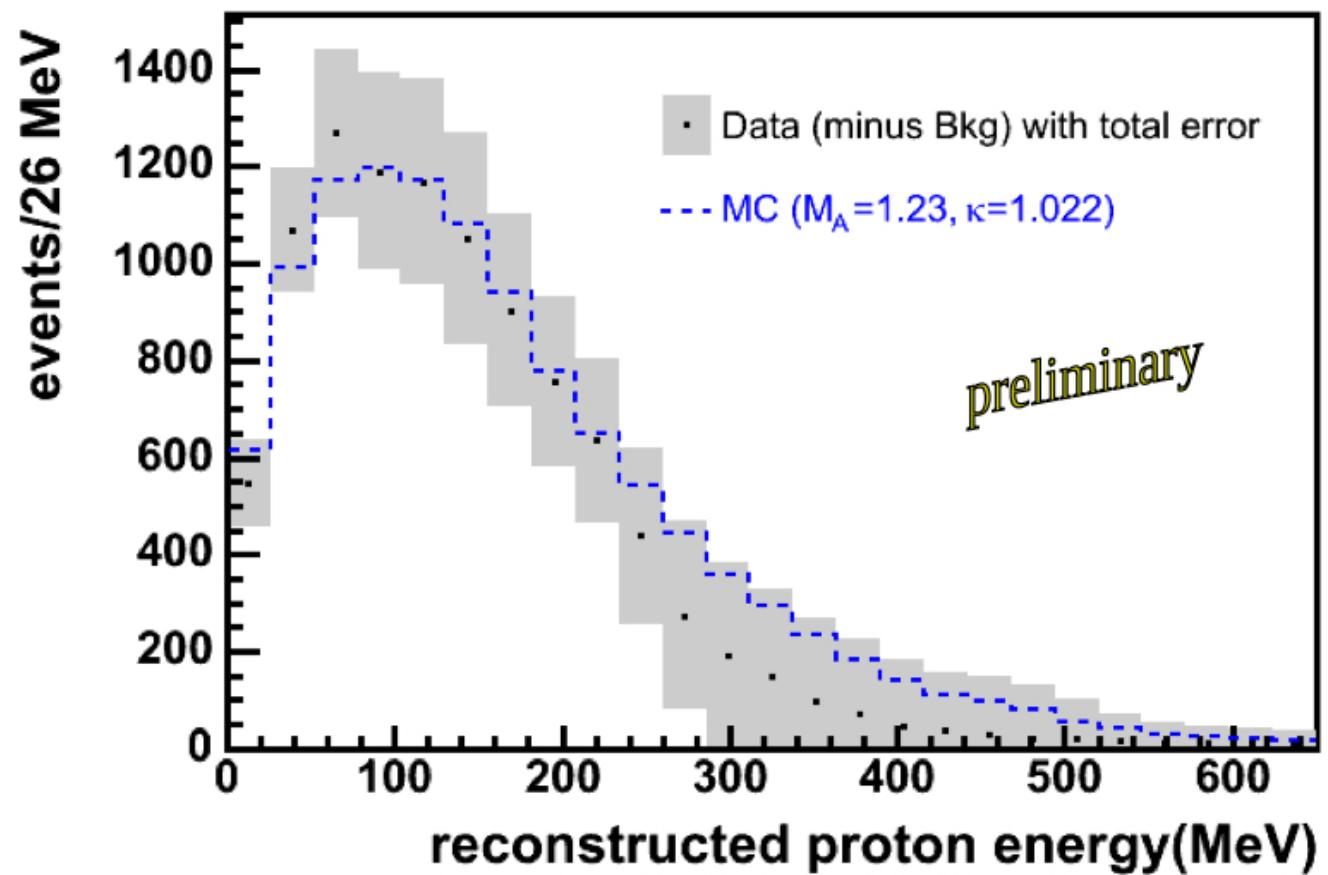
- Neutral current elastic process probes similar formalism as charged-current quasi-elastic
 - sensitive to structure of both nucleon types.
- ▶ Proton fitter developed that reconstructs protons with Scintillation & Cherenkov light ($T_p > 350$ MeV)
- ▶ 94,531 events ($\sim 65\%$ purity)
- ▶ Measured quantities:
 - ▶ $d\sigma/dQ^2$
 - ▶ $\Delta s = 0.08+-0.26$ (strange quark contribution to proton spin)
 - ▶ $M_A = 1.39+-0.11$



Ph.D. thesis, D. Perevalov, University of Alabama
Phys. Rev. D. 82, 092005 (2010)

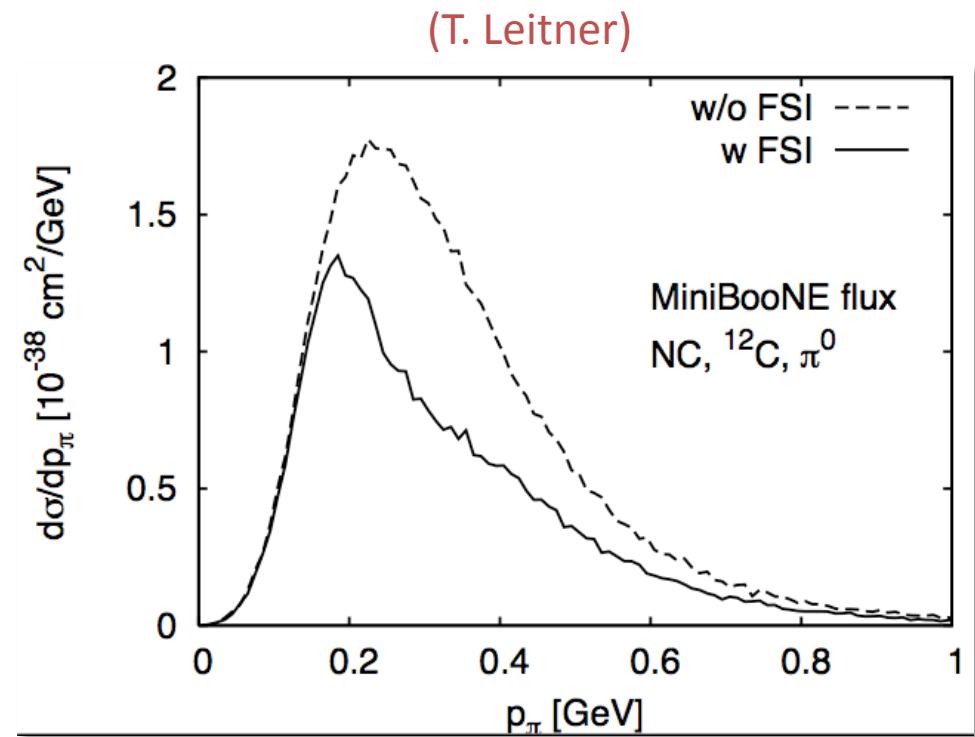
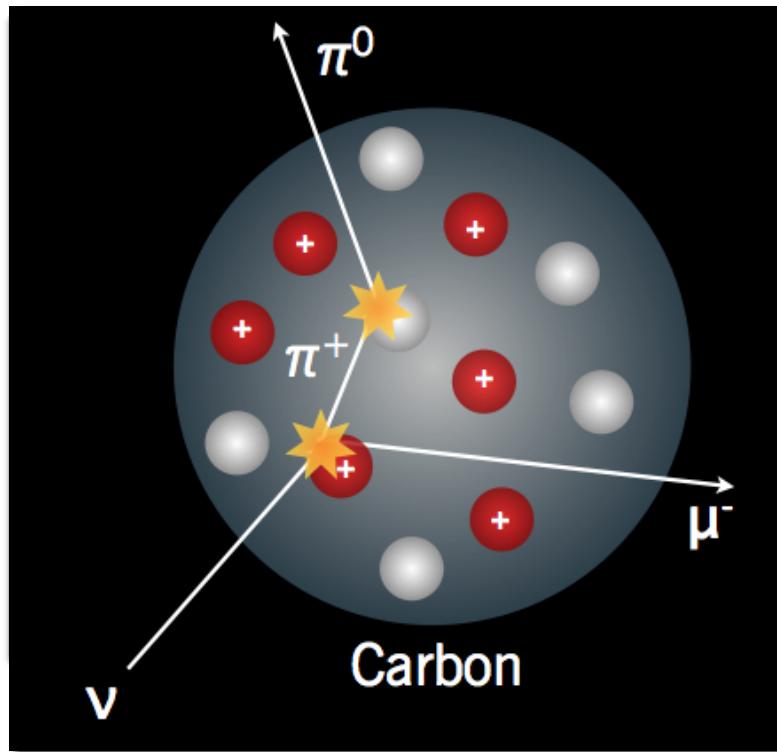
Antineutrino Neutral Current Elastic

- 21,500 events
 $(4.48 \times 10^{20} \text{ POT})$
- 57% $\bar{\nu}$ NC EL purity



(R. Dharmapalan, Nulnt11)

Pion Production Affected by Final State Effects

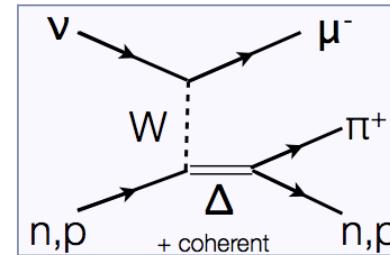


Final State Interactions (FSI): Once produced, hadrons have to make it out of the target nucleus. There can be nucleon rescattering and π absorption & charge exchange. Therefore, we measure final state kinematics in detail and report what we observe.

Charged-Current π^+

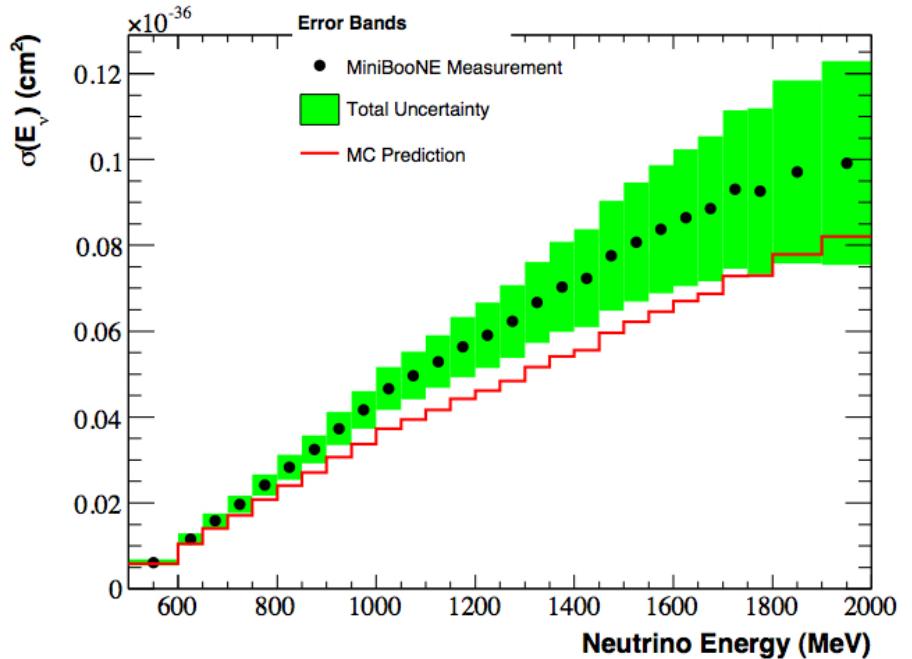
Phys. Rev. D83, 052007 (2011)

- Crucial channel for ν_μ disappearance measurements
 - can bias CCQE signal if π^+ lost



- ▶ First tracking of charged pions in a Cherenkov detector!

- ▶ Measured quantities:
 - ▶ $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$, $d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $d^2\sigma/dT_\mu d\theta_\mu$, $d^2\sigma/dT_\pi d\theta_\pi$ (many firsts)

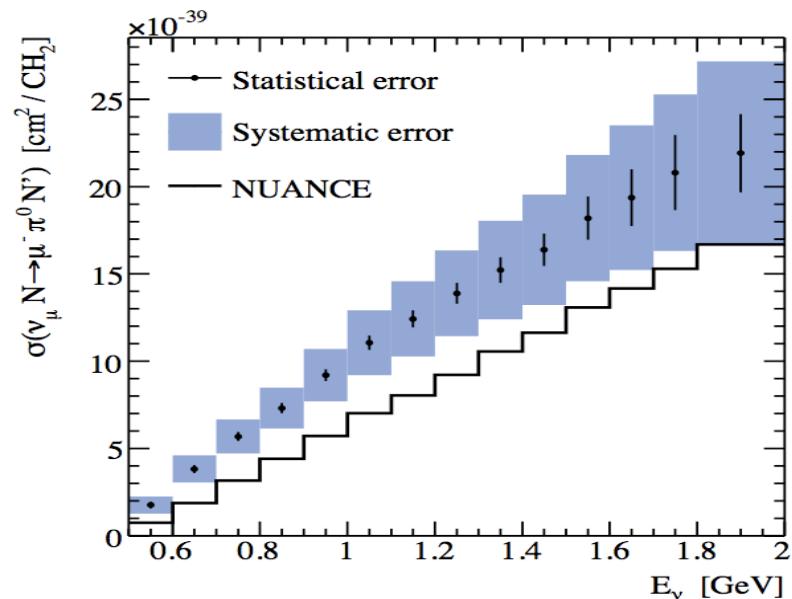
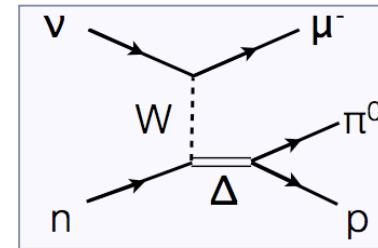
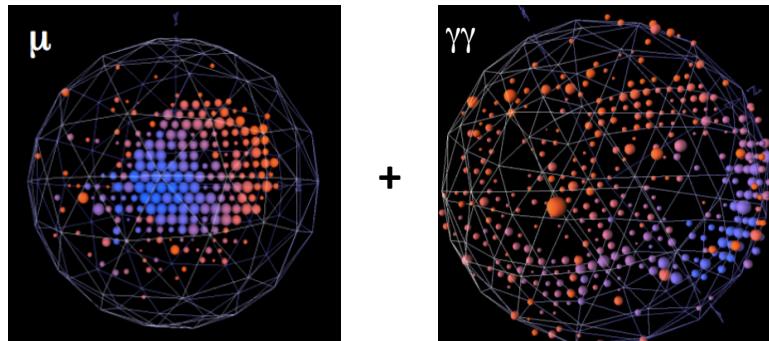


Ph.D. thesis, M. Wilking, University of Colorado
Phys. Rev. D83, 052009 (2011)

Charged-Current π^0

Phys. Rev. D83, 052009 (2011)

- Custom 3 Cherenkov-ring fitter developed to reconstruct both μ , π^0
- ▶ Resonant-only process
- ▶ Measured quantities:
 - ▶ $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$,
 $d\sigma/dp_\pi$, $d\sigma/d\theta_\mu$, $d\sigma/d\theta_\pi$
(many firsts)



Ph.D. thesis, R. Nelson, University of Colorado
Phys. Rev. D 83, 052009 (2011)

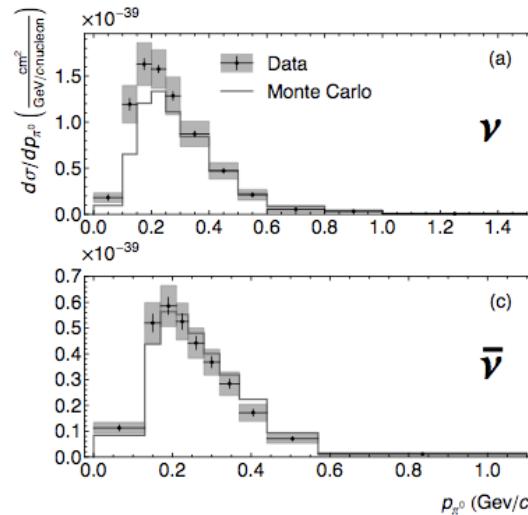
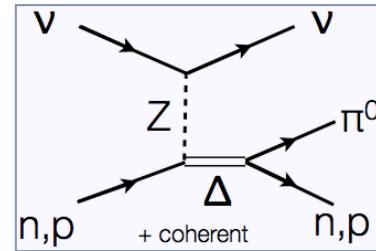
Neutral-Current π^0

Phys.Rev.D81:013005,2010

- Background measurement very important for ν_e appearance analysis
 - NC π^0 signature electron-like if lose γ
 - NC π^0 constrains Δ production which allows for a "measurement" of Δ rad. decay background

- ▶ Valuable input for θ_{13} Cherenkov-based measurements
 - ▶ T2K, LBNE

- ▶ Measured quantities:
 - ▶ $d\sigma/dp_{\pi^0}$, $d\sigma/d\theta_{\pi^0}$
(for both $\nu, \bar{\nu}$ data)

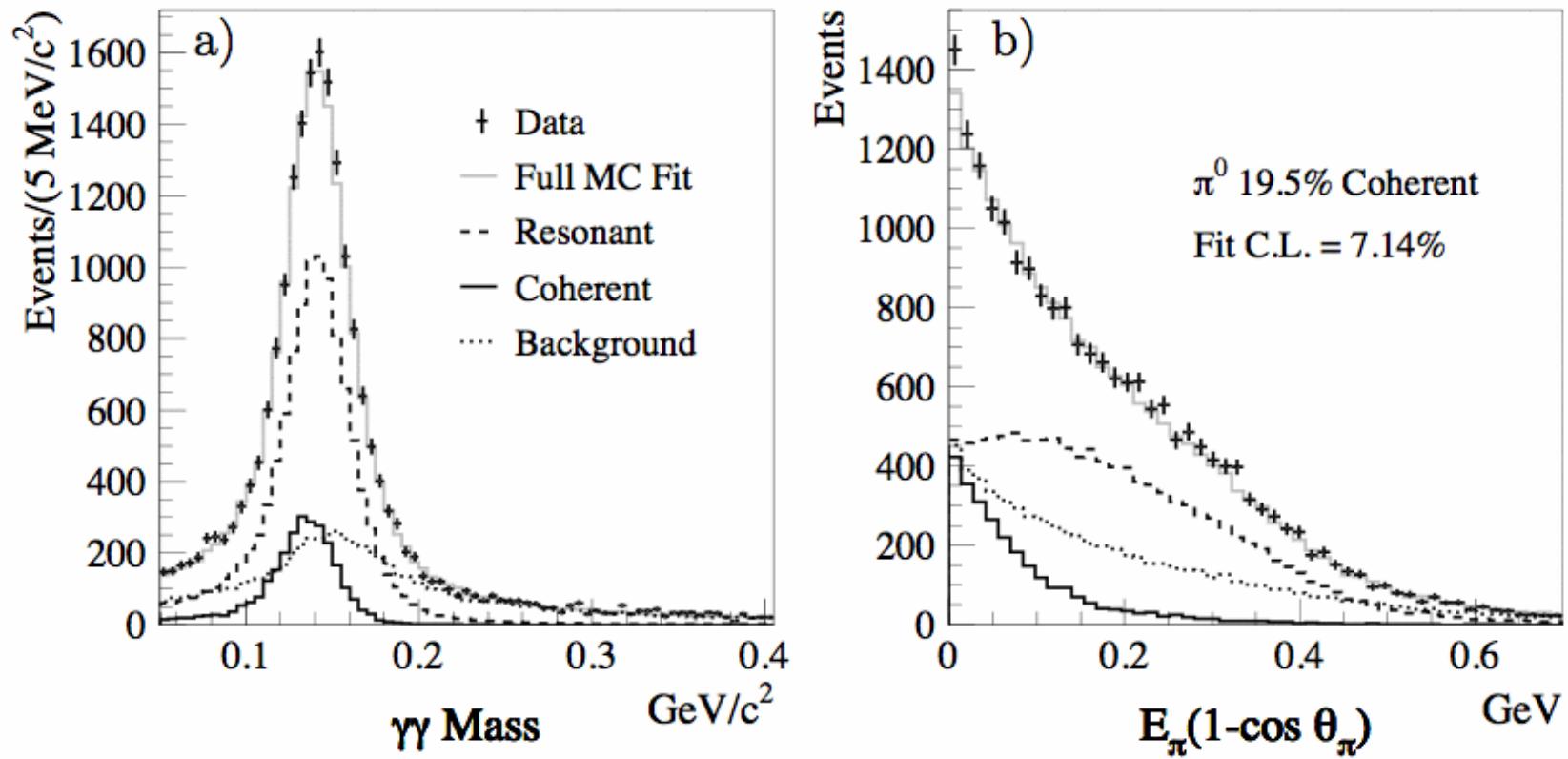


Ph.D. thesis, C. Anderson, Yale University
Phys. Rev. D **81**, 013005 (2010)

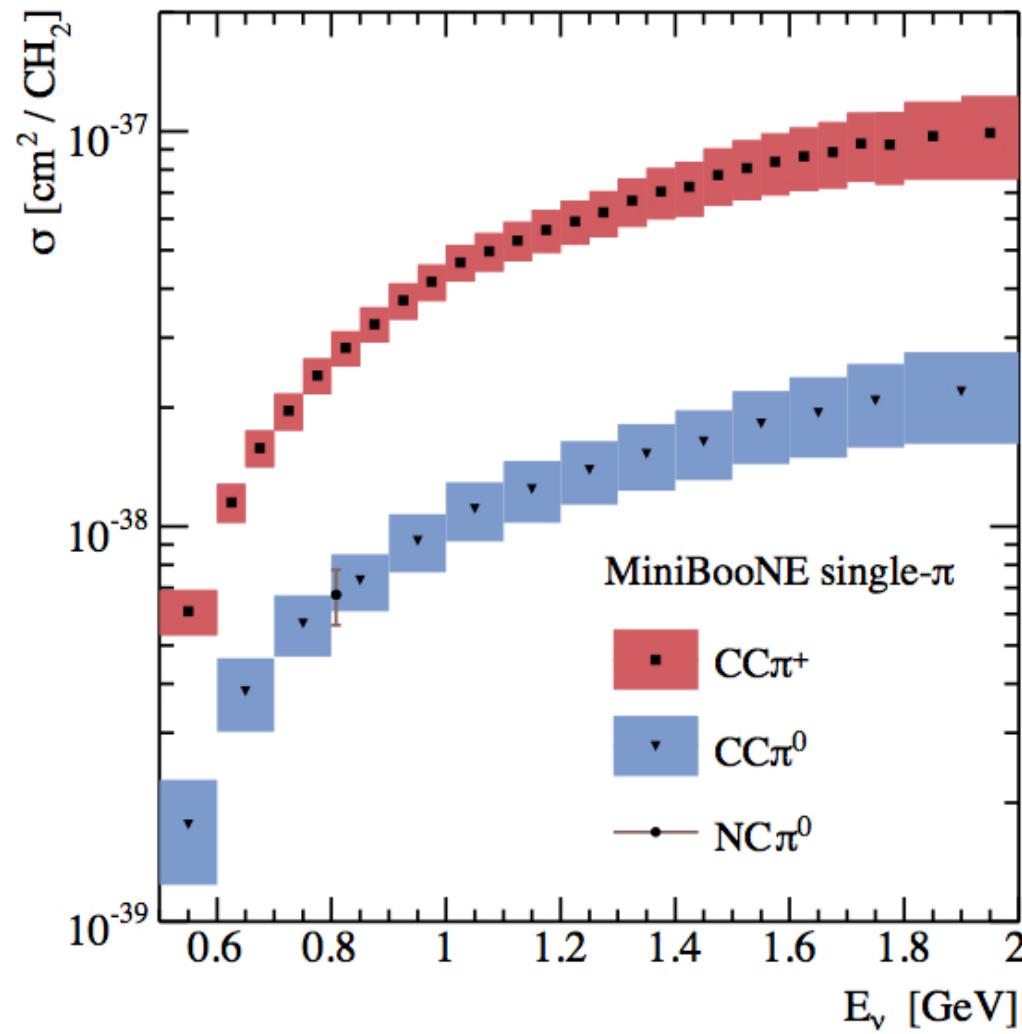
NC π^0 Scattering

A. A. Aguilar-Arevalo et al., Phys. Lett. B 664, 41 (2008)

coherent fraction=19.5+-1.1+-2.5%



Single Pion Cross Sections



(R. Nelson, Nulnt11)

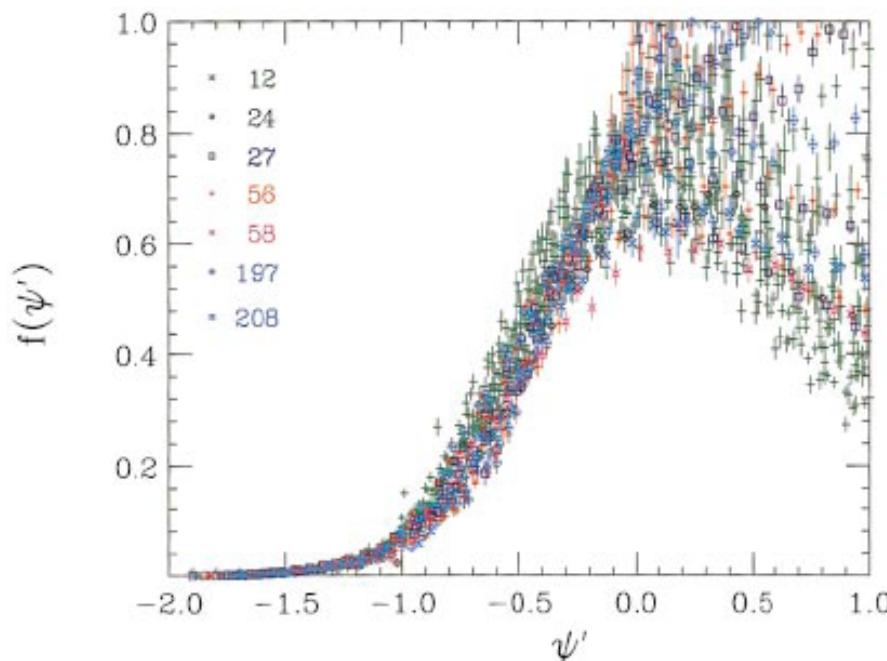
Conclusions

- MiniBooNE Neutrino Cross Sections are more interesting than expected!
- Theorists & Experimentalists must carefully specify what they mean by QE & E_ν , and what is assumed.
- Fermi Gas Model is inadequate for ν -nucleus inclusive scattering.
- Realistic models are required and have to include initial and final state correlations and 2-body currents.
- Differences between neutrino & antineutrino cross sections and energy reconstruction must be better understood when searching for CP Violation.

Backup

Super Scaling

The fact that the nuclear density is nearly constant for $A \geq 12$ leads one to ask, can scaling results be applied from 1 nucleus to another? W.M. Alberico, et al Phys. Rev. **C38**, 1801(1988), T.W. Donnelly and I. Sick, Phys. Rev. **C60**, 065502 (1999)



A new dimensionless scaling variable is employed

$$\psi = \frac{y_{RFG}}{k_{Fermi}} = \frac{m_N}{k_{Fermi}} (\lambda \sqrt{1 + \tau^{-1}} - \kappa)$$

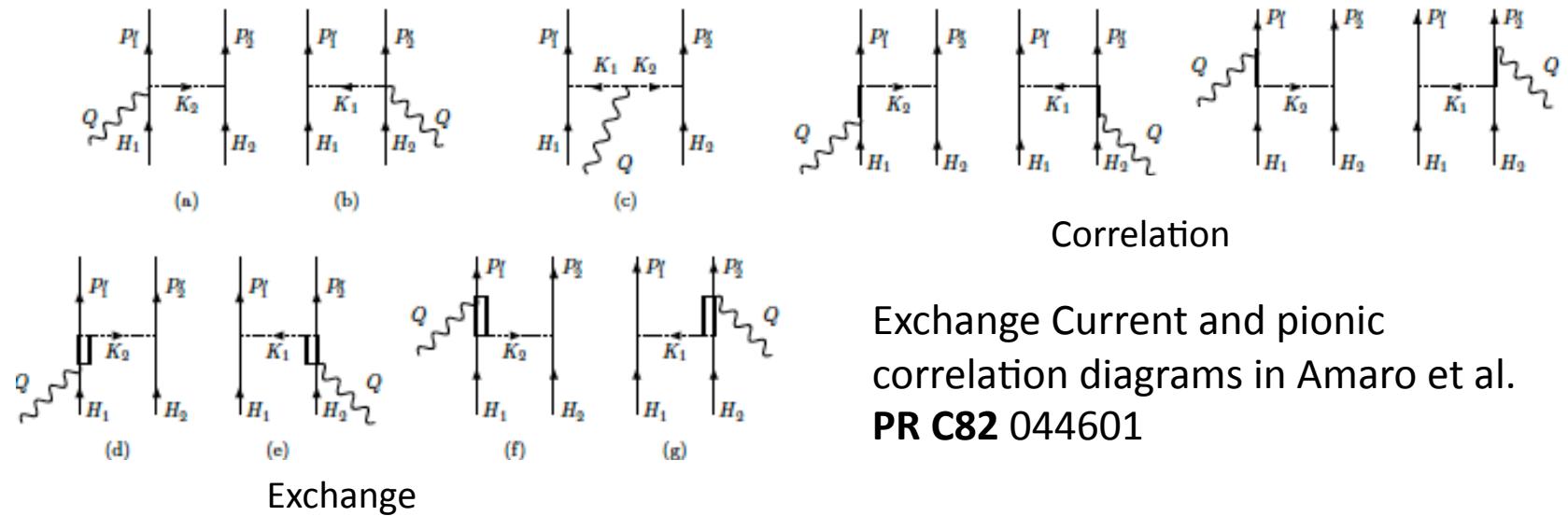
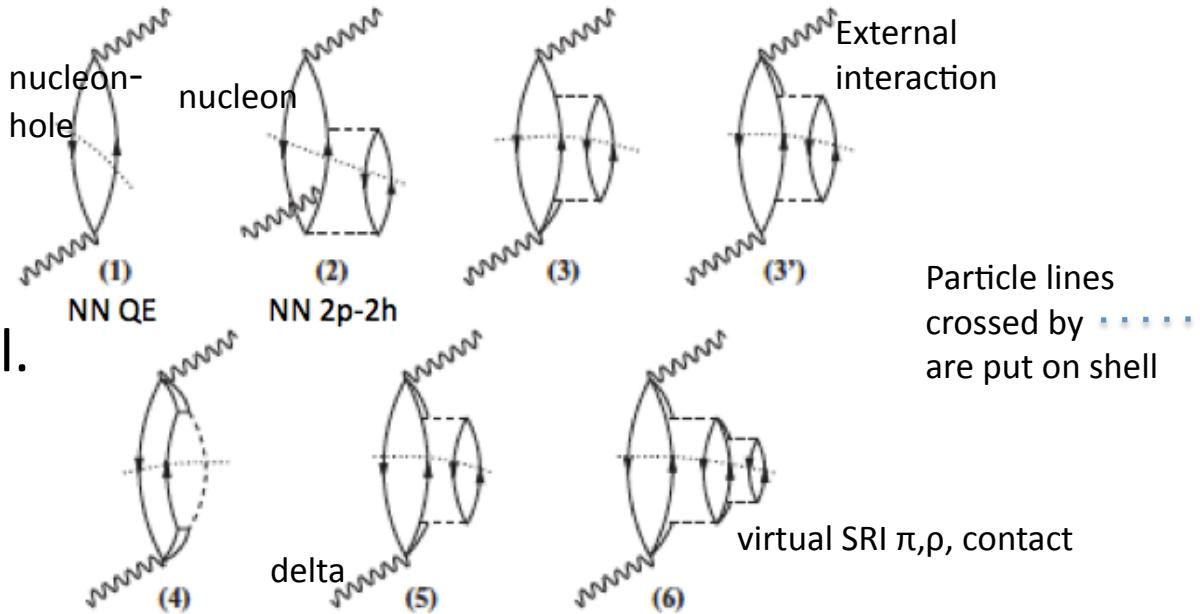
$$\lambda = \omega / 2m_N, \tau = Q^2 / 4m_N^2, \kappa = q / 2m$$

Note linear scale: not bad for
 $\psi < 0$

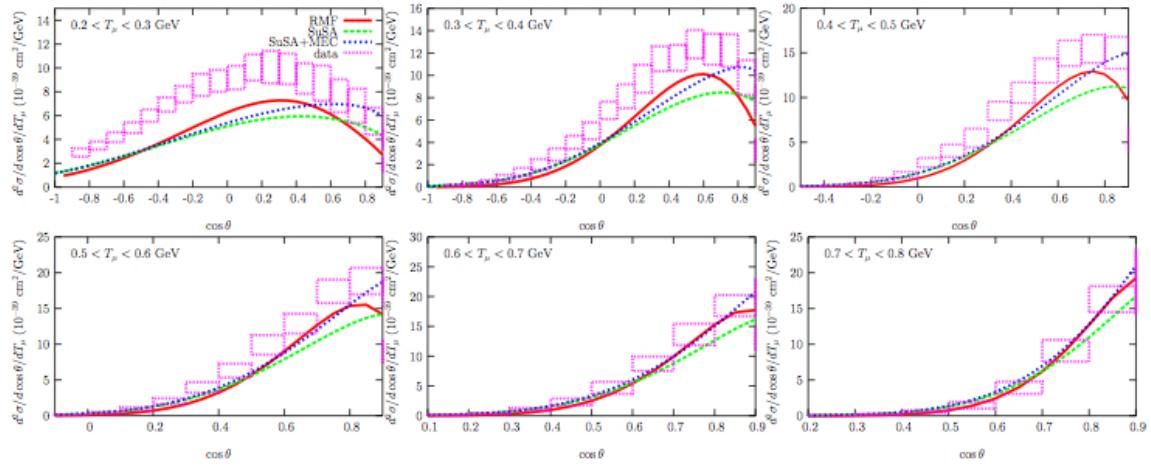
Serious divergence above $\psi = 0$

Diagrams of Some Short Range Correlations

Some RPA p-h
diagrams
from Martini et al.
PR C80, 065501



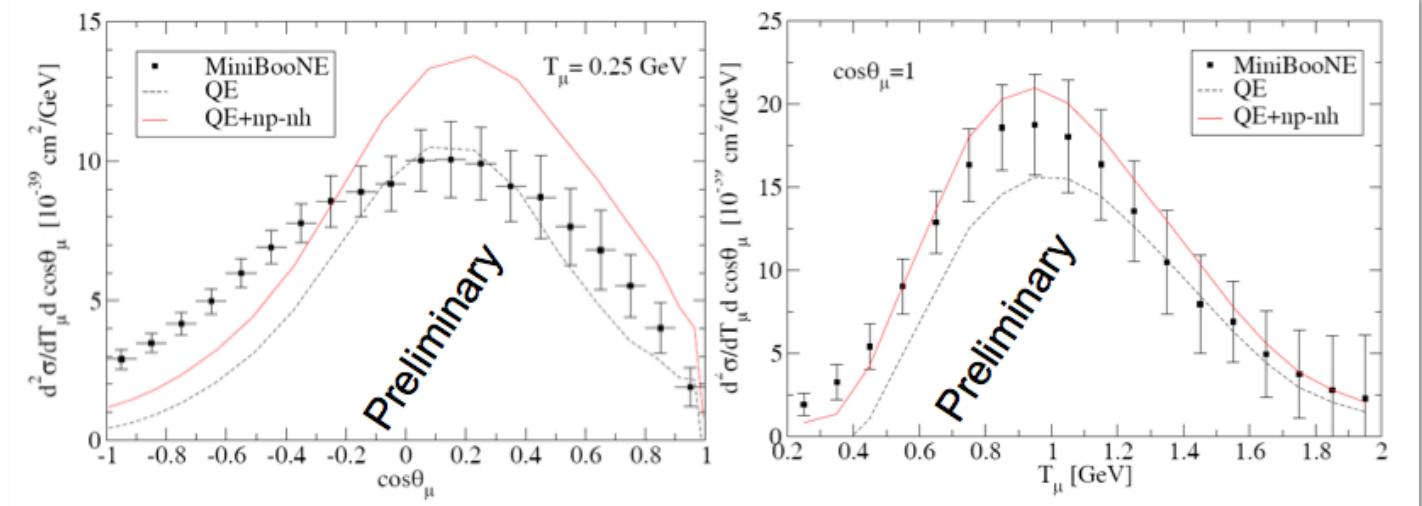
Comparisons to MB Double Diff'l σ



Amaro et al.,
arXiv:1104.5446 [nucl-th]

- underestimate the data at large scattering angles particularly for small T_μ

Martini,
FNAL PPD ν dept.
presentation,
09/30/10



From Sam Zeller

- need more measurements of muon (and proton) kinematics!